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High-spin octupole correlations in the $N=86$, ^{146}Nd and ^{148}Sm nuclei

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High-spin states in ^{146}Nd and ^{148}Sm have been populated using the ^{13}C+^{136}Xe and ^{22}Ne+^{130}Te compound nucleus reactions Alternating parity bands built on the ground state are observed to spin $I=(19)$ and $I=(27)$ in ^{146}Nd and ^{148}Sm respectively Analysis of the data done in terms of the reflection-asymmetric mean-field approach suggests that both nuclei become octupole-unstable at medium spins The observed enhancement of E1 rates supports this prediction In ^{148}Sm also a structure with simplex quantum number $s=-1$ is observed At medium spins the reflection-asymmetric structures coexist with reflection-symmetric configurations The decrease of the electric dipole moment observed for the $N=86$ isotones between $Z=62$ and $Z=64$ is explained by the transition from static to dynamical octupole correlations

In the $84<N<88$ transitional lanthanide nuclei around ^{148}Sm the competition between collective and single-particle modes gives rise to coexistence of various kinds of nuclear excitations. Of particular interest for our work are the octupole excitations observed systematically in this region. These are attributed to the pronounced octupole coupling between $f_{7/2}$ and $i_{13/2}$ neutrons and $d_{5/2}$ and $h_{11/2}$ protons resulting in alternating-parity bands and collective dipole moments observed here [1,2]. Theoretically, nuclei from the Ba–Sm region are predicted by the mean-field calculations to be octupole-soft or even octupole unstable at their ground states [3,4] as well as their excited states [5,2]. According to the theory octupole instability in these nuclei is due to a shell gap, which appears at $Z=62$ for $\beta_3>0$ [5]. Consequently, the effect is not expected for larger Z. As in other $N=86$ isotones, low-lying non-collective states have also been observed in ^{146}Nd and ^{148}Sm [6]. However, while in heavier isotones those states are interpreted as due to a shape change from the collective prolate to a non-collective oblate structure, in ^{148}Sm some of those many-particle excitations are most likely associated with an octupole-unstable configuration. In this letter we want to present new evidence for ^{146}Nd and ^{148}Sm supporting the above predictions.

The measurement of ^{148}Sm has been performed at the Hahn–Meitner Institute, Berlin. High-spin levels in ^{148}Sm have been populated in the ^{130}Te+^{22}Ne reaction using a ^{22}Ne beam of 85 MeV from the VICKSI accelerator. The OSIRIS spectrometer equipped with twelve Ge detectors in anti-Compton shields and a multiplicity filter of 50 BGO crystals was used to measure the γ-radiation from the reaction. In addition the linear polarization of γ-rays from the

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^{138}Ba(^{13}C, 3n)^{148}Sm reaction has been measured using a 55 MeV beam from the tandem of Cologne University. The measurement of ^{146}Nd has been performed at the KVI Groningen bombarding a 3 mg/cm^2 target of solid ^{136}Xe [7] by ^{13}C projectiles of 55 MeV from the cyclotron The γ-radiation was measured using four Compton-suppressed Ge detectors and 10 NaI counters.

The level schemes of ^{146}Nd and ^{148}Sm were established based on the γ–γ coincidence data. In both cases spins were deduced from directional correlation (DCO) ratios [8] found in the present experiments utilizing known spins of low-lying levels [2,9]. For ^{148}Sm the parities of the levels up to spin $I=19$ have been deduced from the linear-polarization measurement. For the stretched quadrupole transitions between high-spin levels in ^{148}Sm, having energies lower than 800 keV, we assumed an E2 character excluding an M2 assignment since no life time longer than 5 ns was observed. The parities of the low-spin levels in ^{146}Nd were taken from ref. [2] and for the high-spin levels in ^{146}Nd they are suggested assuming an E2 character for stretched quadrupole transitions The stretched character of dipole transitions deexciting the 3247 keV and 4789 keV suggest an E1 assignment to these transitions. The level scheme of ^{146}Nd and a partial level scheme of ^{148}Sm as obtained in the present work are shown in fig. 1. The high-spin states in ^{148}Sm have been studied earlier in the ^{148}Nd(α, 4n) reaction [9] and in our previous work using ^{138}Ba(^{13}C, 3n) and ^{150}Nd(α, 6n) reactions [6]. In our previous study of ^{146}Nd [2] we introduced the 849 keV $(8^+)\to 6^+$ transition, which could not be confirmed in the present work

An important result of the present work is an extension of the ground-state bands of alternating parity, having simplex quantum number [12] $s=+1$, to spin $I=(27)$ in ^{148}Sm and to $I=(19)$ in ^{146}Nd, and the observation of enhanced E1 transitions in these bands In table 1 measured $B(\mathrm{E1})/B(\mathrm{E2})$ branching ratios in ^{148}Sm and ^{146}Nd are shown. An average value of the $B(\mathrm{E1})/B(\mathrm{E2})$ ratios in $s=+1$ bands is $1\ 7\times10^{-6}$ fm^{-2} and $1\ 2\times10^{-6}$ fm^{-2} for ^{148}Sm and ^{146}Nd respectively. Using known $B(\mathrm{E2})$ transition rates in these nuclei [10] and assuming that these values stay constant in ground-state bands (see e g. ^{154}Dy [11]) we estimate the average $B(\mathrm{E1})$ rates to be $2\ 2\times10^{-3}$ W u. and 1.5×10^{-3} W.u for the $s=+1$ bands in ^{148}Sm and ^{146}Nd, respectively. These results indicate an enhancement of E1 transitions in both nuclei At medium spins $B(\mathrm{E1})/B(\mathrm{E2})$ ratios are larger, suggesting stabilization of octupole effects with increasing spin.

The enhancement of octupole collectivity in both nuclei is reproduced by the Woods–Saxon–Bogolyubov cranking calculations with an axially deformed, reflection-asymmetric mean field [12–14]. In octupole-unstable nuclei theory predicts an increase of the intrinsic electric dipole moment [13,14], which could explain the enhancement of E1 transitions in the $s=+1$ bands The average D_0 values for the ground-state bands in $N=86$ isotones are shown in fig. 2. The D_0 values for $Z\geqslant60$ were calculated as $D_0=[\frac{5}{16}B(\mathrm{E1})/B(\mathrm{E2})]^{1/2}Q_0$, taking average $B(\mathrm{E1})/B(\mathrm{E2})$ ratios from table 1 and refs. [15–17] and Q_0 from ref [10] For $Z<60$, D_0 moments were taken from ref. [18]. Our work gives for ^{146}Nd $D_0=0.18(1)$ and for ^{148}Sm $D_0=0\ 13(1)$ for spins $I\leqslant7$ (full point) and $D_0=0.22(2)$ for spins $8\leqslant I\leqslant16$ (open point in fig 2) The experimental data are compared to the predictions of reflection-asymmetric Woods–Saxon model. The dashed line corresponds to calculations at $I=0$ with the ground-state equilibrium deformations taken according to ref [19]. The predicted values of D_0 representative for medium spins, $I\sim6$, are indicated by a solid line computed using equilibrium deformations obtained in ref. [5]. The $N=86$ isotones of Ba, Ce and Nd are predicted to have reflection-asymmetric ground states. According to the calculations the octupole-deformed configuration is lowered at medium spins, which results in larger octupole deformation and large D_0 moment The nucleus ^{148}Sm lies on the border of the region of octupole instability. It is predicted to be weakly quadrupole-deformed at $I=0$ but it gains quadrupole and octupole collectivity at higher spins. The predicted dipole moment at $I\sim6$ is quite large. It is because the proton and neutron contributions to D_0 add coherently for $Z=62$ and $N=86$–88, (see refs. [13,5]). Octupole-deformed shapes in Sm isotopes can be associated with the large single-particle gap at $Z=62$, which opens up for $\beta_3>0$ [5]. For $Z>62$ calculations do not predict static reflection-asymmetric shapes, hence $D_0=0$. On the average, the reflection-asymmetric mean-field approach reproduces experimental data surprisingly well. Of course, the results

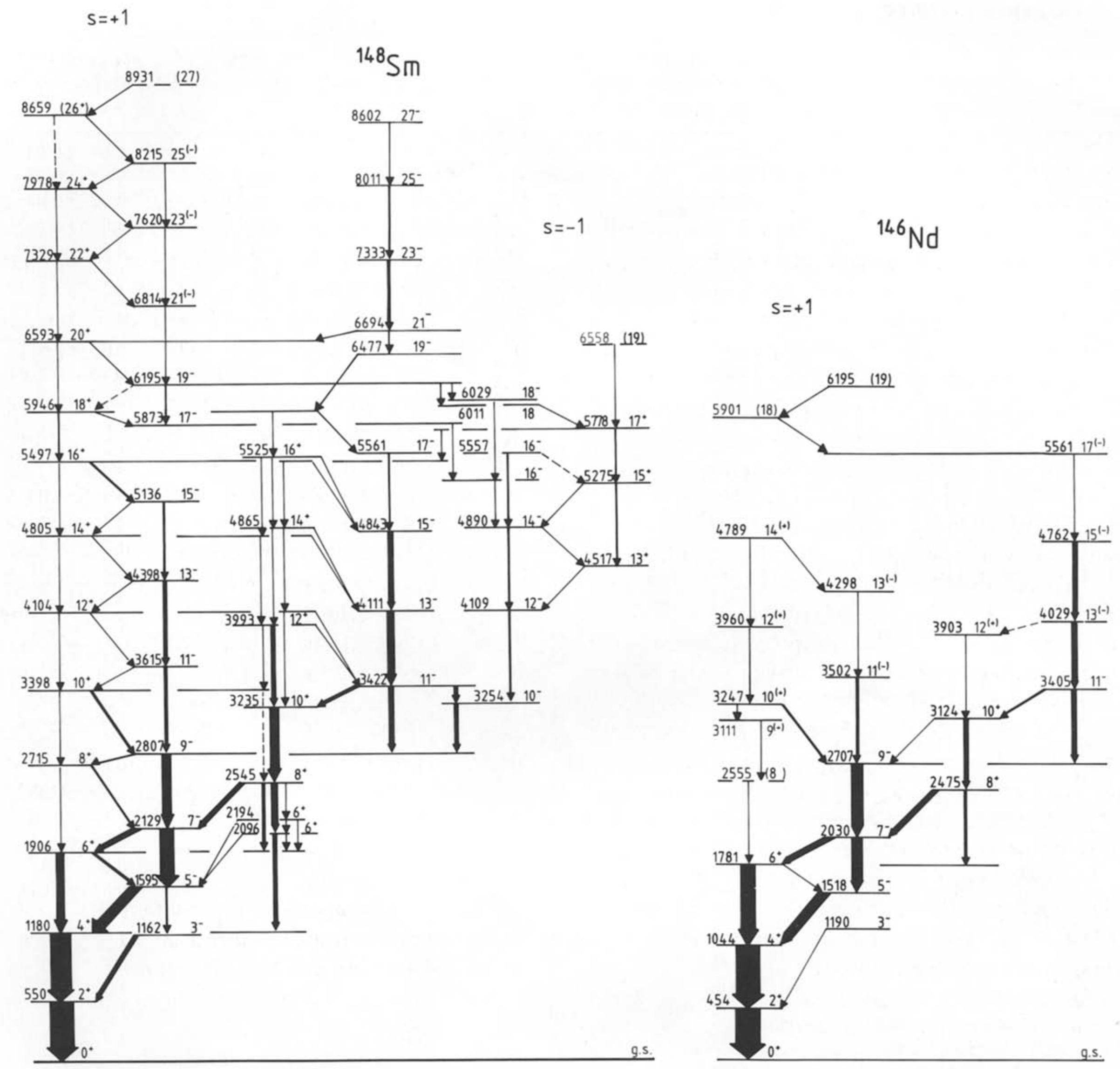

Fig 1 Level scheme of ^{146}Nd and partial level scheme of ^{148}Sm

of calculations presented in fig. 2 should be considered as a static limit. Dynamical fluctuations associated with the coupling to low-lying quadrupole and octupole vibrations are expected to play a significant role, especially for $Z \geqslant 64$, where they are responsible for large values of $\langle D_0^2 \rangle$ (see e.g. ref. [20]).

Another interesting result of our work is the observation of a second alternating-parity sequence in ^{148}Sm. The spin–parity assignments for the sequence above the 10^-, 3254 keV level were unambiguously determined using DCO and linear polarization measurements. The $B(\mathrm{E1})/B(\mathrm{E2})$ ratios are here of the same order as for the $s=+1$ band (see table 1). This observation indicates a strong octupole mixing involved and suggests a simplex $s=-1$ classification for this structure. This is the first firm observation of such a band.

Looking for a possible interpretation of this struc-

Table 1
Experimental $B(\mathrm{E1})/B(\mathrm{E2})$ ratios in ^{146}Nd and ^{148}Sm

		Initial level		$E_\gamma(\mathrm{E1})$ [keV]	$E_\gamma(\mathrm{E2})$ [keV]	$B(\mathrm{E1})/B(\mathrm{E2})$ [10^{-6} fm^{-2}]
		E_{exc} [keV]	I^π			
^{148}Sm	$s=+1$ band	1595	5^-	414	443	0.68 ±0.04
		1906	6^+	312	726	0.81 ±0.05
		2129	7^-	223	534	0.62 ±0.04
		2715	8^+	586	809	0.8 ±0.1
		2807	9^-	92	679	4.9 ±0.9
		3398	10^+	591	683	1.5 ±0.3
		3615	11^-	217	807	2.9 ±0.3
		4104	12^+	490	706	5.1 ±1.2
		4398	13^-	293	783	1.9 ±0.4
		4805	14^+	407	701	0.9 ±0.2
		5136	15^-	331	738	0.4 ±0.1
		5497	16^+	360	691	1.2 ±0.2
		5946	18^+	109	450	1.2 ±0.2
		6195	19^-	249	358	<0.025
		6592	20^+	398	647	0.11 ±0.03
		7329	22^+	416	737	<2.3
		7620	23^-	291	707	1.7 ±0.5
		7978	24^+	357	648	0.8 ±0.3
		8214	25^-	237	549	4.5 ±1.5
	$s=-1$ band	4890	14^-	373	781	1.1 ±0.1
		5275	15^+	385	758	0.7 ±0.1
	other branchings	2096	6^+	502	915	1.22 ±0.07
		2194	6^+	600	1014	1.9 ±0.5
		2545	8^+	416	639	1.8 ±0.08
		3422	11^-	187	615	10.4 ±0.5
		3993	12^+	571	757	0.49 ±0.05
		4104	12^+	682	706	0.19 ±0.05
		4805	14^+	694	701	0.06 ±0.01
		5497	16^+	654	691	0.8 ±0.1
		5946	18^+	385	450	0.05 ±0.01
^{146}Nd	$s=+1$ band	1518	5^-	475	(329)	>1.0
		1781	6^+	262	737	0.9 ±0.2
		2030	7^-	250	512	1.3 ±0.1
		3247	(10^+)	540		>1.5
		4789	(14^+)	494	(828)	1.4 ±0.2
	other branchings	2475	8^+	445	694	2.6 ±0.9
		3124	10^+	417	649	0.21 ±0.04
		3405	11^-	281	699	0.68 ±0.05

ture as well as irregularities observed in the $s=+1$ band around spin $I=18$ let us note that in both ^{146}Nd and ^{148}Sm there is a strong competition between octupole and non-collective excitations, the latter being observed systematically in the $N=86$ isotones [9,15,21]. In table 2 we show some of the probable assignments for levels in ^{146}Nd and ^{148}Sm. The structures on top of the 8^+ states at 2475 keV and 2545 keV and 11^- states at 3405 keV and 3422 keV in ^{146}Nd and ^{148}Sm respectively, correspond most probably to a nearly spherical, reflection-symmetric configuration since E1 transitions feeding these levels from the $s=+1$ band are an order of magnitude slower than those within the $s=+1$ band (cf. table

Table 2
Single-particle configurations in ^{146}Nd and ^{148}Sm

Level E_x [keV] ^{146}Nd	^{148}Sm	I^π	Configuration
2475	2545	8^+	$\{\nu[(f^3_{7/2}), h_{9/2}]_{8^+}\pi(d^{-2}_{5/2})_{0^+}\}_{8^+}$
	3254	10^-	$\{\nu(i_{13/2}, f^3_{7/2})_{10^-}\pi(d^{-2}_{5/2})_{0^+}\}_{10^-}$ and $\{\nu[(i_{13/2}, h_{9/2})_{10^-}(f^2_{7/2})_{0^+}]_{10^-}\pi(d^{-2}_{5/2})_{0^+}\}_{10^-}$
3405	3422	11^-	$\{\nu[(i_{13/2}, h_{9/2})^{max}_{11^-}(f^2_{7/2})_{0^+}]\pi(d^{-2}_{5/2})_0\}_{11^-}$
(5901)	5946	18^+	$\{\nu[(i^2_{13/2})_{12^+}, (f^2_{7/2})_{6^+}]^{max}_{18}\pi(d^{-2}_{5/2})_{0^+}\}_{18^+}$
	6593	20^+	$\{\nu(i^2_{13/2})_{12^+}(h_{9/2}, f_{7/2})_{8^+}]^{max}_{20^+}\pi(d^{-2}_{5/2})_{0^+}\}_{20^+}$
	6694	21^-	$\{[\nu(i_{13/2}, h_{9/2})^{max}_{11^-}(f^2_{7/2})_{0^+}]\pi(h^2_{11/2})^{max}_{10^+}\}_{21^-}$

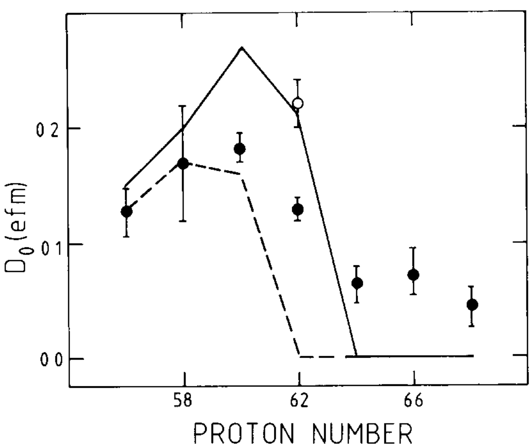

Fig 2 Plot of the electric dipole moment D_0 as a function of proton number for the $N=86$ isotones For ^{148}Sm the full (open) points represent an average value of D_0 for spins $I \leqslant 7$ ($8 \leqslant I \leqslant 16$) The theoretical prediction of the reflection-asymmetric Woods–Saxon model is indicated by the dashed ($I=0$) and solid ($I \sim 6$) line

1). The situation is different for structures built on the 10^-, 3254 keV and the 18^+, 5946 keV levels. These levels are also interpreted as single-particle configurations. However alternating-parity bands built on top of them show large $B(E1)/B(E2)$ branching ratios, which are of the same order as those in the lower part of the $s=+1$ band. In our opinion these observations indicate a new coupling scheme where a simplex structure is based on an octupole-unstable many-quasiparticle configuration

The results obtained in the present work for ^{148}Sm indicate a new physical situation where octupole modes are mixed with *both*, collective and non-collective high-spin excitations. Furthermore, the observation of low-lying, non-collective excitations implies that this nucleus is γ-soft and may behave as heavier $N=86$ isotones where shape changes from the collective prolate to non-collective oblate structures have been observed. Therefore ^{148}Sm is a good candidate to test the rotation-induced interplay between reflection asymmetry and triaxiality.

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